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PROTECTION OF SHIPBOARD PERSONNEL AGAINST THE
EFFECTS OF SEVERE SHORT-LIVED UPWARD FORCES
RESULTING FROM UNDERWATER EXPLOSIONS

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January 1960

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FINAL REPORT
ON
NAVY CONTRACT NAONR 104-51

PROTECTION OF SHIPBOARD PERSONNEL AGAINST THE EFFECTS OF
SEVERE SHORT-LIVED UPWARD FORCES RESULTING FROM UNDERWATER
EXPLOSIONS

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ABSTRACT

Relative strength of the legs at various knee angles was determined in the standing position by three different test procedures. Man's weakest knee angle was found to be 60° .

X-ray studies of the legs and feet during vertical loading failed to reveal any bending of the femur or tibia or compression of cartilages in the knee or ankle. There was a slight lateral bending of the fibula and the tarsal and metatarsal bones were displaced downward.

Human voluntary tolerance to vertical impact were determined while (1) standing with knees locked, (2) standing with knees bending, (3) squatting, and (4) seated in a rigid chair. In addition, various energy-dissipating materials and devices were evaluated for protection against vertical impact. These tolerances and evaluations are summarized in Table I.

This exploratory study of man's tolerance to vertical deceleration was divided into three phases:

- I. Determination of relative strength of the legs at various angles of knee flexure.
- II. Study of deformation of joints and long bones of the legs by double exposure X-rays of subjects static loaded with weights.
- III. Determination of man's voluntary tolerance to vertical impact forces in drop tests

and

Evaluation of various energy-dissipating materials for protection against vertical impact.

PHASE I. Determination of Relative Strength of the Legs
at Various Angles of Knee Flexure.

Three different test procedures were used to establish knee angle strength:

- A. Thirteen subjects wearing a knee protractor (Fig. 1) were asked to slowly squat from the standing position while bearing across his shoulders the near maximum bar bell weights he could lift from approximately 140° . Motion picture records were made of the 50 squatting tests and analyzed to determine the breaking point (i.e., the knee angle at which the squatting movement suddenly accelerated). Note the protractor measures the angle of the thigh from the vertical. These angles were converted to knee angle by subtracting from 180° .
- B. Leg strength at small knee angles was measured by having the same subjects try to lift the bar bell weights from a full squatting position. Maximum angle of extension of the knee from this position was recorded in 67 tests on the 13 subjects.
- C. In addition 171 static measurements of maximum leg strength were made with knee angles of 30, 45, 60, 90, 120, 150, and 180° with dynamometers mounted as shown in Figure 2. Knee angles were measured by placing one arm of a goniometer along the anterior surface of the thigh and the other on the anterior aspect of the leg.

I. RESULTS AND CONCLUSIONS:

Results of the three test procedures are shown in Figure 3. The upper and lower limits of static lift forces are shown for all subjects by broken lines with the mean represented as a solid line. Low point on the curve is at about 60° (180 lbs. av.) and the highest point at 160° (550 lbs. av.). Note that the curve falls off at 180° since the legs are straight and this represents a measurement of toe lift.

The limits for all subjects in the lift from squat tests are shown by the shaded area at the left ($45-60^{\circ}$) while the shaded area on the right represents the range of angle of break for all subjects in the slow squat tests ($60-80^{\circ}$). The results show that man's weakest knee angle is around 60° and the knee angles for greatest strength lie between 100 and 160° .

Distribution of vertical impact loads by bending the knees must be accomplished by muscular contractions and relaxations while going down from 160° to 60° knee flexure.

PHASE II. Detection of deformation of joints and long bones
of the legs during static loading.

Figure 4 shows the arrangement used for making double exposure X-rays of one leg. The first exposure was made with the subject supporting most of his body weight by his arms so that the leg to be X-rayed was essentially unloaded. For the second exposure 250-300 lbs. of weights were lowered on the subjects. Four sets of X-rays were made on each of the ten subjects - front and side views of the knee area and front and side views of the foot and lower leg. A sample X-ray is presented in Figure 5.

With this loading there was no detectable bending of the femur or tibia or compression of the cartilages in the knee or ankle. However, there appears to be a slight lateral bending of the fibula, and the tarsal and metatarsal bones are displaced downward about one-quarter of an inch. There is a slight flattening of tissues under the heel (Os calcaneum).

PHASE III. Determination of Man's Tolerance to Vertical Impact.

PURPOSE AND METHOD:

It was the purpose of this study not only to determine vertical impact tolerance by progressive increments of impact loading but also to record transmissibility and attenuation of the impact force to the areas of the body where pain limited tolerance.

The voluntary tolerance limit (the point where one or more subjects complained of severe pain) was established for three body positions: (1) Standing - a. knees locked, b. knees allowed to flex, (2) Squatting, and (3) sitting.

Nearly 500 drop tests were made with 13 human subjects on the apparatus shown in Figure 6 which consisted of a hoist, trip mechanism and drop platform with a guiding track. The base platform mounted on leaf springs with hydraulic pistons for damping was instrumented with strain gauges and had a maximum motion of one inch.

"G" forces and jolts at the point of impact were recorded from a Consolidated Electrodynamics Corporation electrokinetic accelerometer attached to the floor of the drop platform. A second accelerometer taped to the top of the shoulder recorded forces transmitted to the head and upper trunk area. The CEC accelerometer with a range of 0.01 - 1000 g, 5 cps to 40 kc in conjunction with a cathode ray oscillograph proved satisfactory for recording input loads while a Statham ± 10 g was found more satisfactory for readings at shoulder level.

DISCUSSION:

Subjects complained of severe pains in the chest, stomach, lower spine and head when the shoulder accelerometer recorded 10 g at slightly over 600 g per sec. regardless of body position during the impact (i.e. standing with knees locked or seated on a rigid chair). However, input loads to produce this deceleration at shoulder level varied with the body position being 65 g and 10,000 g/sec. while standing with knees locked (Fig. 7,8) and 95 g and 19,000 g/sec. while seated on a rigid chair (Fig. 9). This, as well as the difference in the transmission rate of the impact (See Summary Table I), might be explained by the extreme rigidity of the skeletal system in the standing position as compared to the compressibility of the gluteal musculature while seated.

When subjects were allowed to flex the legs to distribute the deceleration (Fig. 10) they were able to sustain impact loads of 250 g and 50,000 g/sec. without limiting pains. Further increases in the impact loading was prohibited by the height of the drop mechanism, but shoulder readings of 7 g and 583 g/sec. indicates that the subjects were nearing the deceleration that produces chest pains. It is worthy of note that impact loads of this magnitude produced extreme bruising and soreness of the feet when subjects wore thin-soled street shoes but was scarcely noticeable when they wore combat boots with 1/2" leather soles.

When subjects were dropped in the squatting position (Fig. 11) limits of voluntary tolerance were reached when the shoulder accelerometer recorded only 5 g and 250 g/sec. with input loads of 133 g and 26,600 g/sec. At this level no pain was experienced in the head or trunk but tolerance was limited by severe pains in the knees and musculature of

the upper and lower legs. Apparently, the flexing muscles of the knee were acting as a fulcrum trying to pry open the knee joint and over extend the extensor muscles causing strain on their attachments.

Numerous materials and methods were studied to increase the deceleration time and increase man's tolerance in the seated position.

The rigid chair was modified by hinging the front edge of a second seat bottom above the first in such a manner that test materials could be inserted between the two at the back edge and near the contact area of the buttocks (Fig. 12).

The relative merits of stayfoam, styrofoam, polyvinyl chloride, undrawn nylon, horsehair and rubber, and hydraulic bleed pistons were investigated.

Tests on undrawn nylon were discontinued after many trials as its behavior seemed unpredictable. Difficulties were encountered with the material slipping from its clamps or breaking without stretching. In two tests the material performed properly and seemed to do a good job of distributing the impact load over a longer period of time. This material should be investigated further.

In the brief time allotted to studying the use of hydraulic pistons none were found that could bleed fast enough to be effective in increasing man's tolerance. However, this should not be taken to preclude the possibility of using such a device.

The polyvinyl chloride proved unpredictable and had a tendency to splinter or break rather than crush.

Four-inch horsehair (bonded with rubber) cushions similar to those used on some aircraft are a slight improvement over the rigid seat.

Blocks of styrofoam were placed between the two seat bottoms (supporting surface 15 sq. in., height before compression = 4 inches, depth of compression = 1-7/8 inches). Subjects rated this arrangement about equal to the horsehair cushion.

Very good results were obtained with a single block of stayfoam 7 1/2 inches high and 4" x 4" in cross section (Fig. 12, 13). Impact loads of 220 g and 44,000 g/sec. produced accelerations of 9 g and 250 g/sec. in the shoulder area with no symptoms of pain in any of the subjects and crushed the block three inches. Height of the dropping equipment did not allow for further testing at higher impact loadings. This material looks extremely promising as a means of increasing man's tolerance to vertical impacts. Stayfoam 1900 series are semi-rigid formulations manufactured by the Dayton Rubber Company. Formulae 1901 was used in these tests. Again referring to Fig. 12 it should be noted that the stayfoam will be compressed by the man's weight before impact unless a simple mechanism - catch or shear pin - is provided. For the test procedure, two strands of wrapping cord proved satisfactory.

Input loads discussed above refer only to the initial peak while the actual deceleration pattern usually consisted of three high frequency positive peaks with negative peaks between. Complete deceleration curves are presented in Figures 8 through 13.

Attenuation and rate of transmission of the impact loads through the body were analyzed for various body positions and are presented in Table I. In the rigid drops (i.e. - standing with knees locked and seated on a rigid chair) there is very little attenuation

(6-10x) and a very rapid transmission (400-1000 ft./sec). This serves to illustrate the extreme rigidity of the human framework. On the other hand impact forces were attenuated 36 times by bending the knees, 25x by stayfoam in the seat, and 29x in the squatting position. The rather high transmission rates (250 ft/sec) in impacts with knees bending probably occurred during the initial adjustment of muscle tension as subjects by reflex action attempted to absorb most of the impact before reaching the weaker knee angles (See Fig. 3). Also, it should be noted at this point that athletes made very rapid adjustment during this period and were able to equalize the impact loads and distribute them evenly over a period of time. Non-athletes either held the knees too rigid at the point of impact and received higher initial jolts or too relaxed with the result that they lost the initial advantage of the stronger knee angles and "hit bottom."

RESULTS AND CONCLUSIONS:

1. Best position for shipboard personnel during periods of danger of deck blast is seated in chairs equipped with energy-dissipating materials and restraining harness and/or belt. The stayfoam block discussed in this report increased man's natural tolerance in a rigid chair about tenfold and the author feels that further testing with this and similar materials could further increase his tolerance many times. After the first few tests with stayfoam subjects were instructed not to use the seat arms as it became apparent there was danger of arm and shoulder injury as the seat compressed the stayfoam block. Seat arms, if used, should be designed to move downward with the seat pan and be of a non-rigid construction as we have learned that chest injuries from impact with rigid seat arms cause many fatalities in airplane crashes.
2. While a first analysis the squatting position appears favorable for absorption of deck blast, the authors feel certain that impact loads in excess of those described in the text for this position would produce incapacitating knee injuries. Hence, shipboard personnel should be instructed to avoid the common and restful practice of squatting when there is danger of deck blast.
3. If it becomes absolutely necessary to stand during periods of danger personnel should be instructed never to stand with one leg stiff and one knee bent - a natural resting stance - since forces will be transmitted practically undiminished through the stiff leg. Instead, they should stand with both knees slightly bent (as in parade rest) with weight equally distributed on both feet.
4. Present thin-soled oxfords should be replaced with heavy-soled -

above the ankle - shoes, similar to the common work shoe.

5. Athletics and calisthenics should be encouraged to develop leg strength, muscle coordination, and reaction time.

TABLE I. SUMMARY OF VOLUNTARY TOLERANCES TO VERTICAL IMPACT

Body Position	MAXIMUM VOLUNTARY TOLERANCE AS MEASURED AT SHOULDER LEVEL			LOADING APPLIED AT POINT OF IMPACT			PHYSIOLOGICAL SYMPTOMS	TRANSMISSION (IMPACT - SHOULDER)		
	Peak g	Onset g/sec.	Duration of Deceleration sec.	Peak g	Onset g/sec.	Duration of impact		Attenuation	Time (Sec.)	Velocity ft/sec.
1. Standing Knees Locked	10	666	.04	65	10,000	.008	SEVERE PAIN IN: Chest, stomach, small of back, hip joints, top of head. PAIN IN: Arches, back of legs, ankles, heels, throat	6.5	.005	1,000
2. Seated in Rigid Chair	10	625	.057	95	19,000	.0075	SEVERE PAIN IN: Chest, spine, head, stomach, SHOCK: Severe - general.	9.5	.0085	410
3. Standing Legs Flexing	*7	583	.16	250	50,000	.0075	SHOCK IN: Feet SLIGHT PAIN IN: Ankles, calves, fore thighs, sides and fronts of knees.	36	.02	250
4. Squatting	5	250	.20	133	26,600	.0075	SEVERE PAINS IN: Knee joints, anterior thighs, calves, front of lower legs, heels	29	.03	83
5. Seated in Chair equipped with Starboard	*9	250	.12	220	44,000	.0065	PAIN - NONE SLIGHT SHOCK IN: Stomach.	25	.024	146

* Not Maximum Tolerance - Test Limited by Height of Drop Mechanism

TABLE II. Anthropometric Measurements of Subjects (N = 13)

	Age	Weight (lbs.)	Height (inches)	Sitting Ht. (Anth)	Trunk Ht.	Buttocks Knee	Patella Ht.	Abdominal Girth	Thigh Circumfer- ence	Chest Depth	Abdominal Depth
Mean	22	171.3	71.10	35.90	23.50	24.60	22.10	33.20	20.70	9.23	8.70
Median	21	170.0	71.00	36.00	23.50	24.50	22.00	33.00	20.75	9.25	8.50
Q ₁	20	156.0	69.75	35.25	22.75	23.50	21.50	31.75	20.00	8.75	8.13
Q ₃	24	191.5	73.00	36.50	24.13	25.38	22.63	35.25	21.38	9.75	9.50

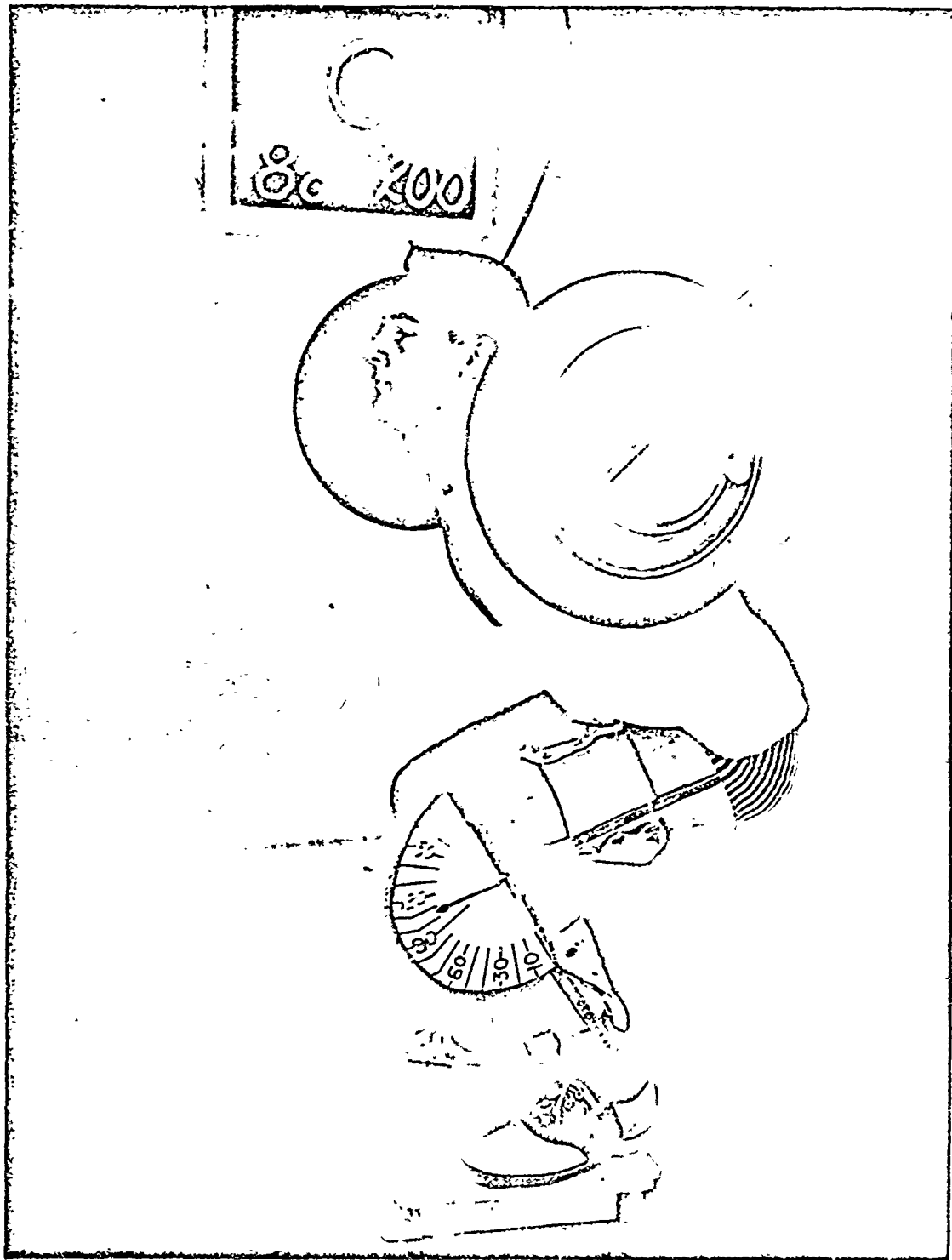


FIG.1. Subject performing squat test with 200 lbs. while wearing knee protractor.

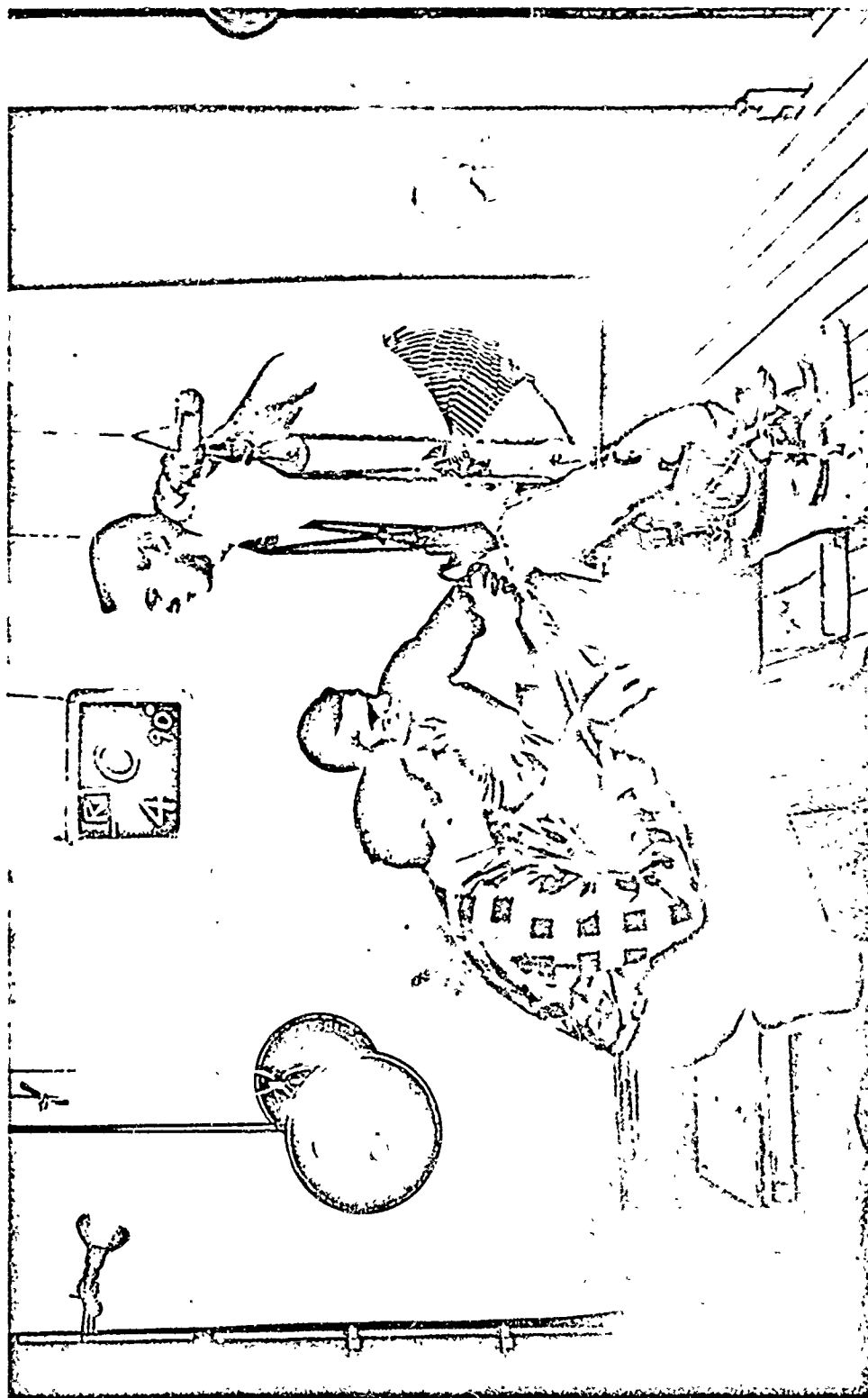


FIG. 2. Apparatus used for determining static lifting strength of legs with various degrees of knee flexure.

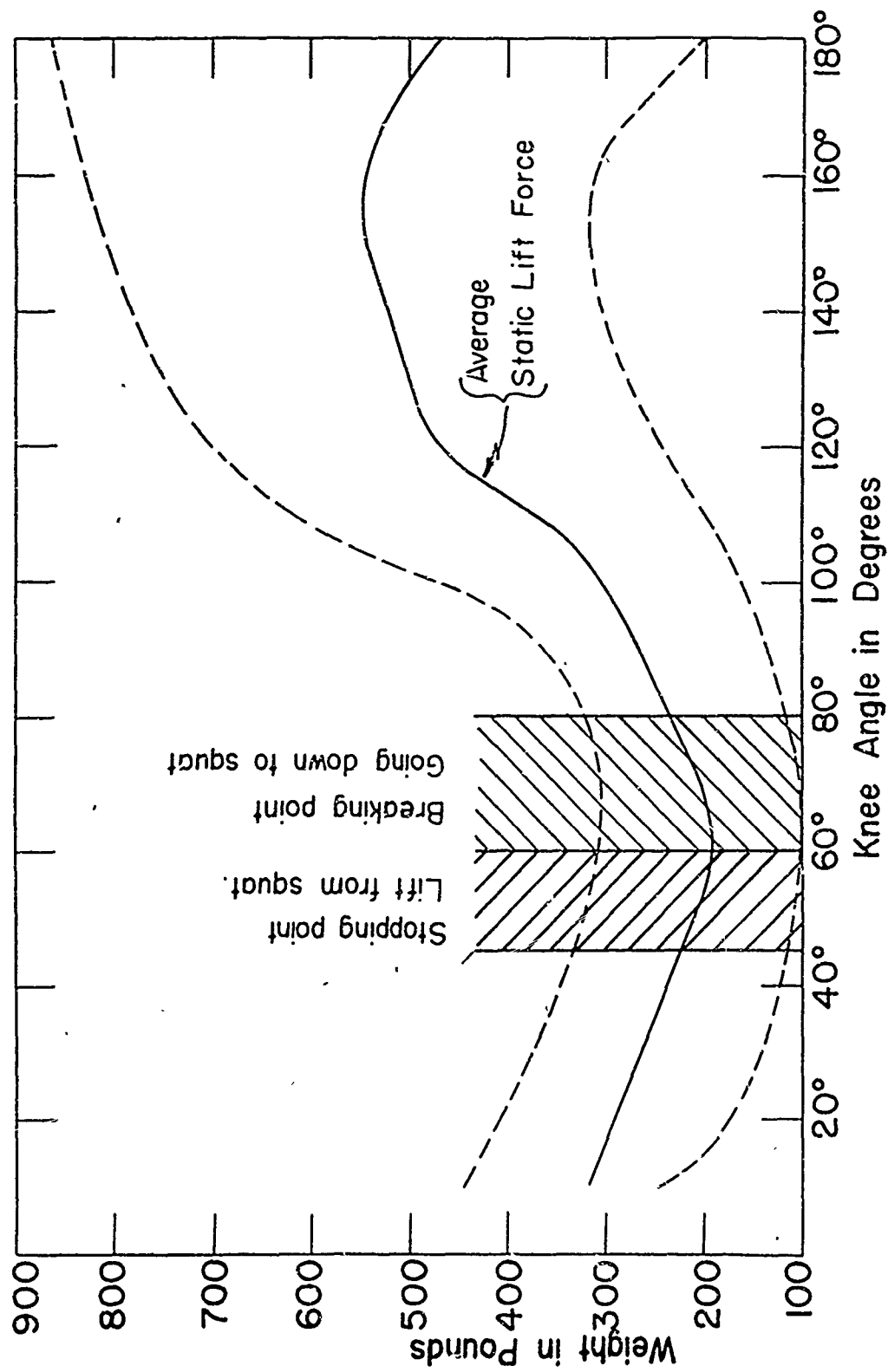


Fig.3 RELATIVE LEG STRENGTH WITH VARIOUS KNEE ANGLES



FIG. 4. Arrangement for making X-ray studies of leg bones during static loading.

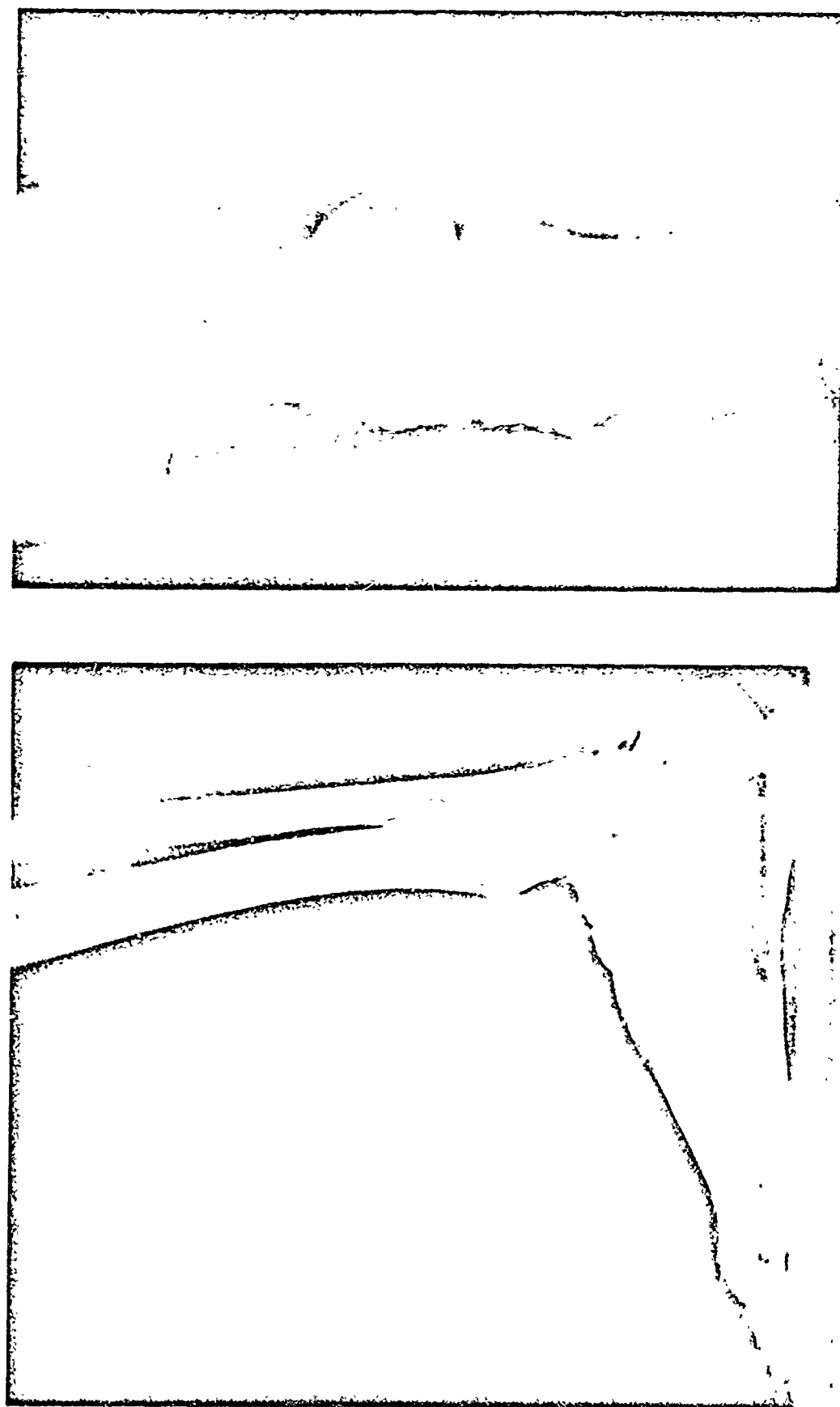


FIG. 5_ Double exposure X-ray of bones of the
lower leg with and without static load.

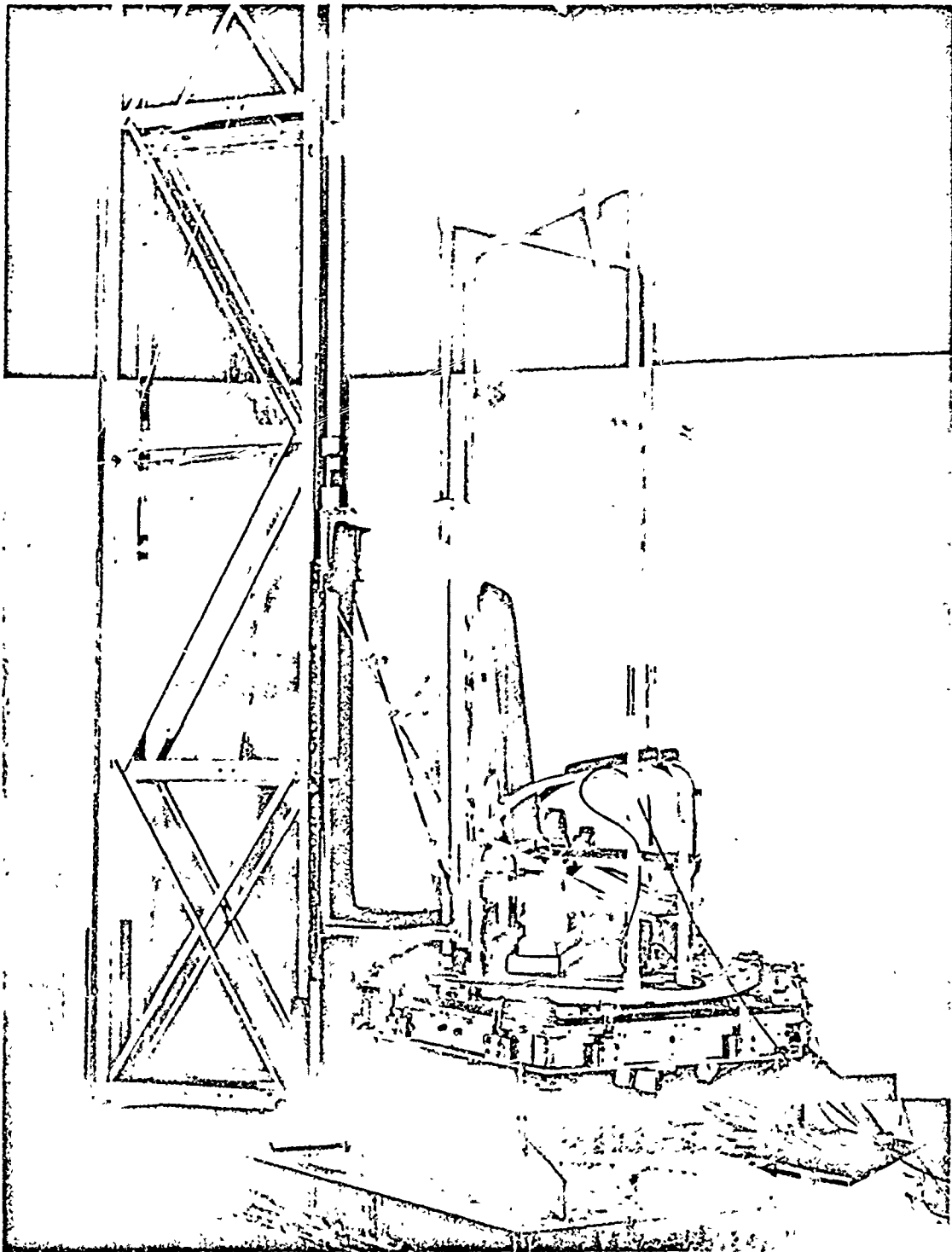


FIG. 6. Drop test apparatus.

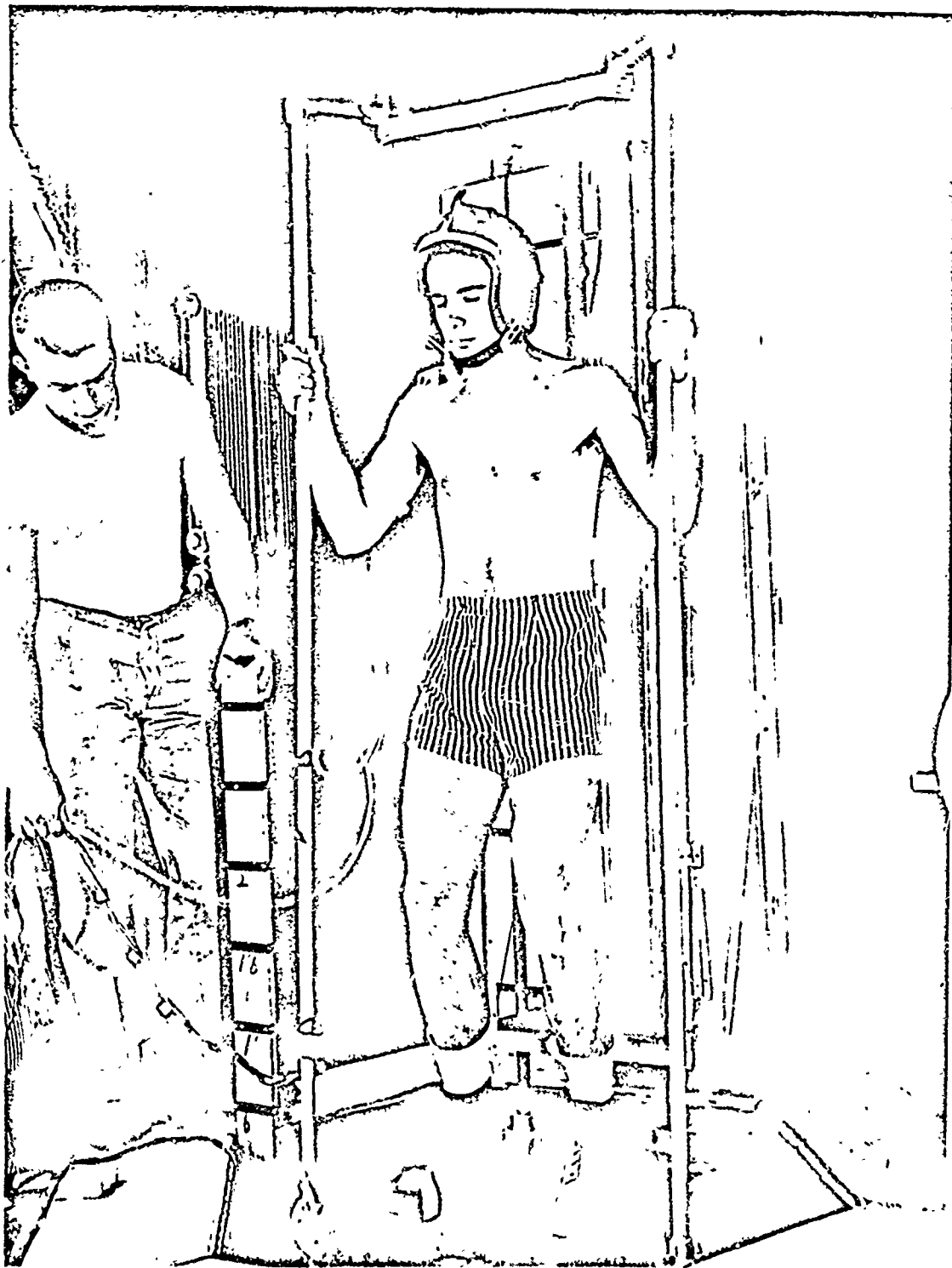


FIG. 7. Subject experiencing impact in the standing position.

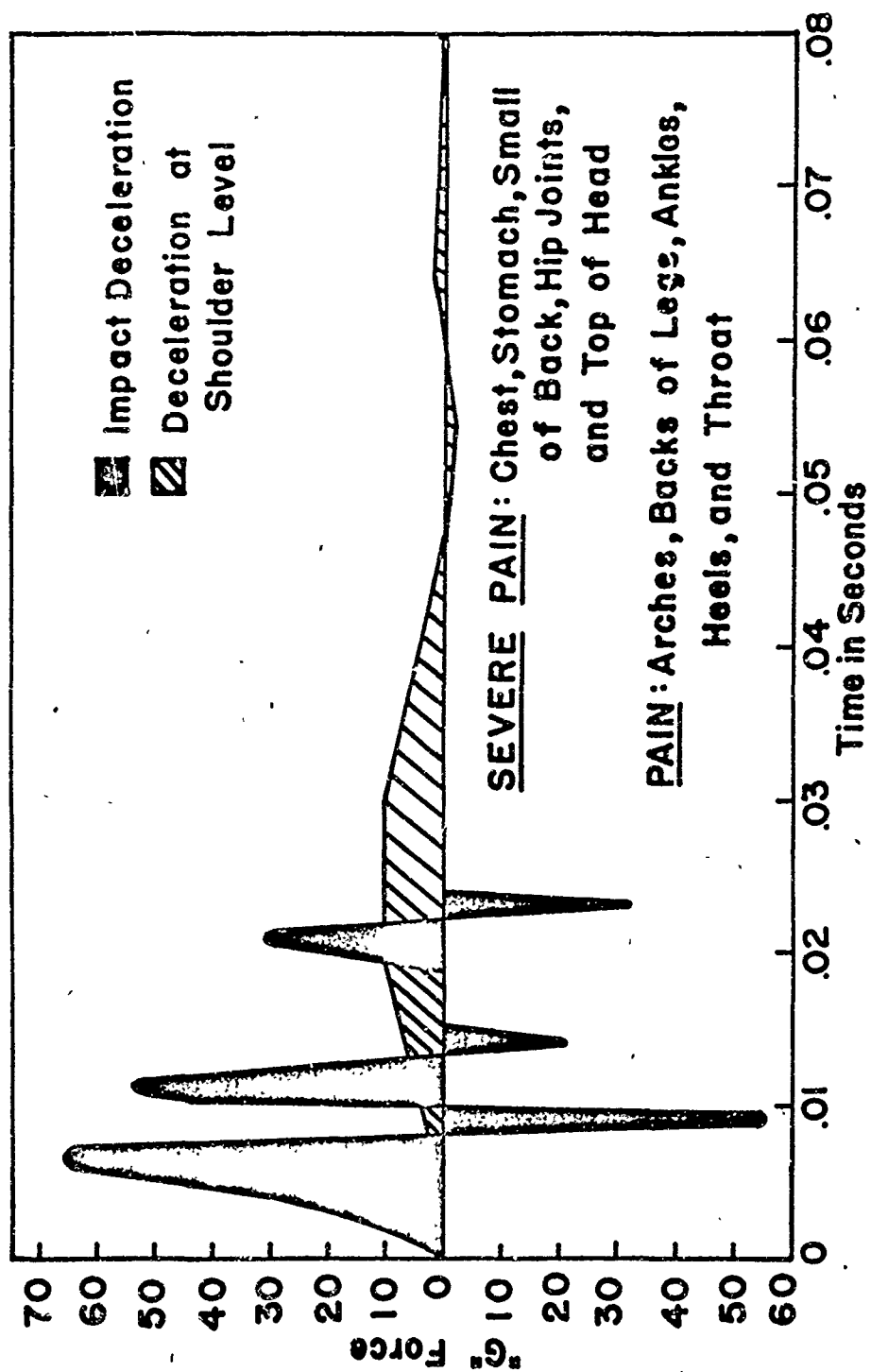
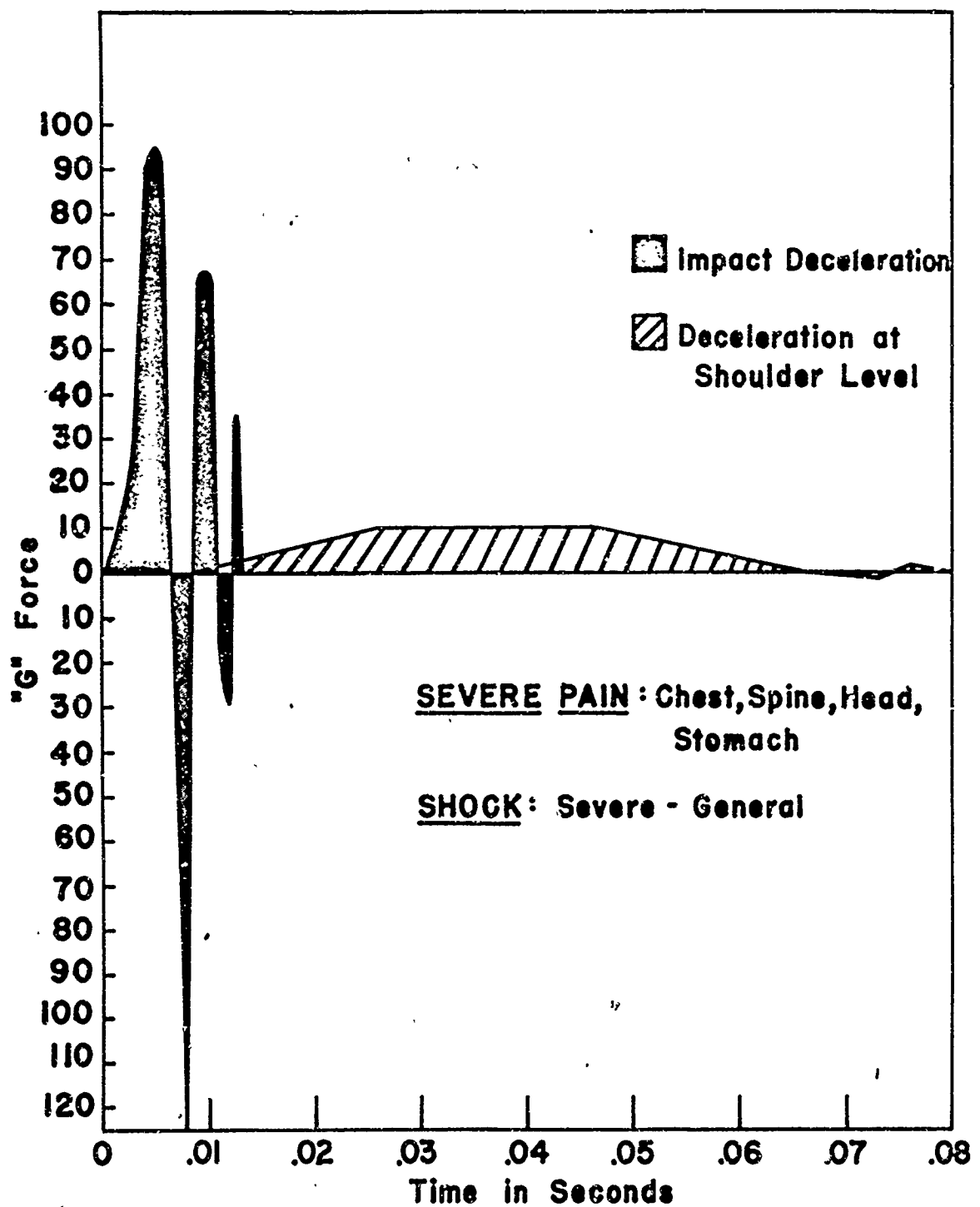


Figure 8 VERTICAL IMPACT DECELERATIONS
Standing - Knees Locked



**Figure 9 VERTICAL IMPACT DECELERATIONS
Seated in Rigid Chair**

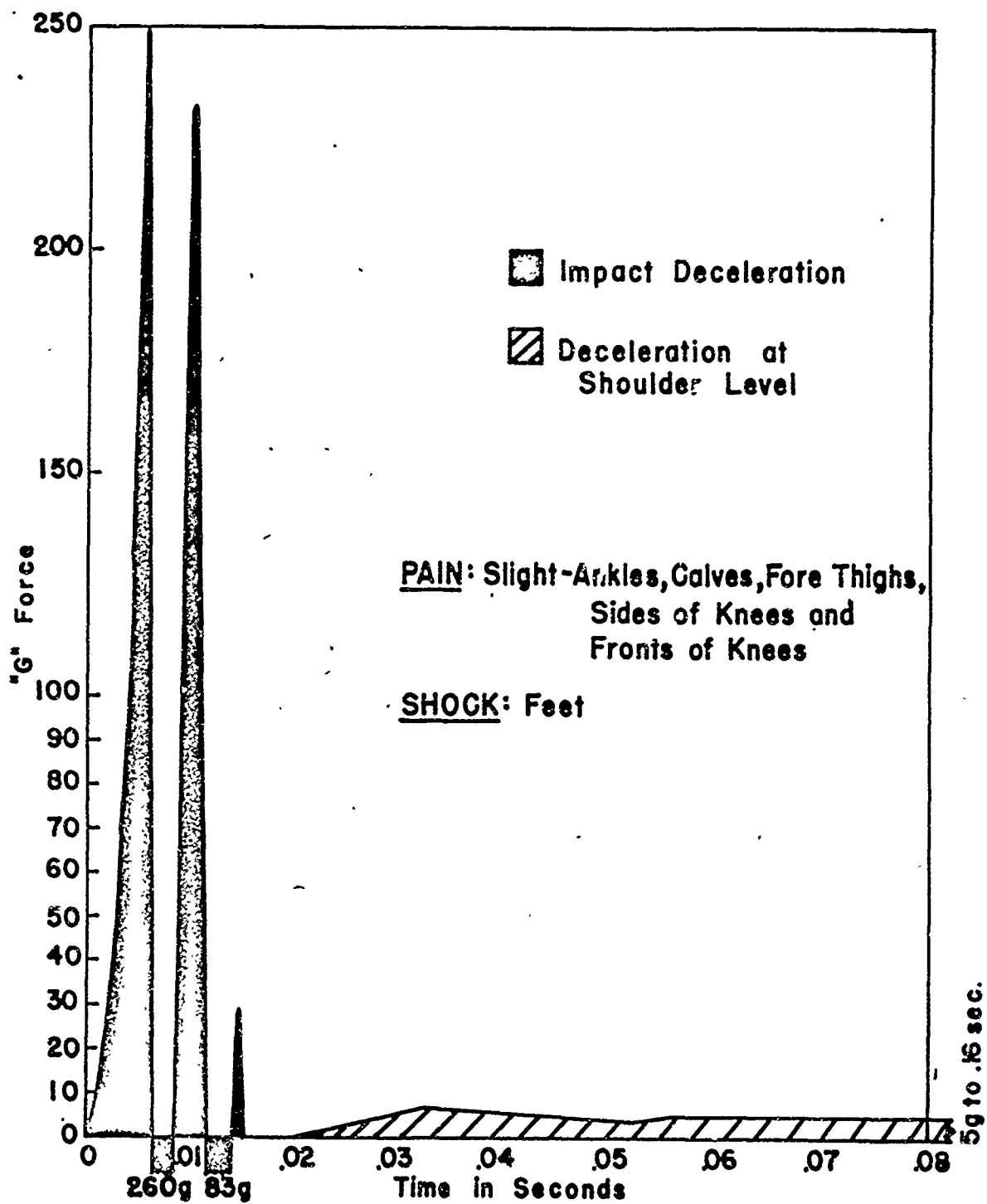


Figure 10 VERTICAL IMPACT DECELERATIONS
Standing - Legs Flexing

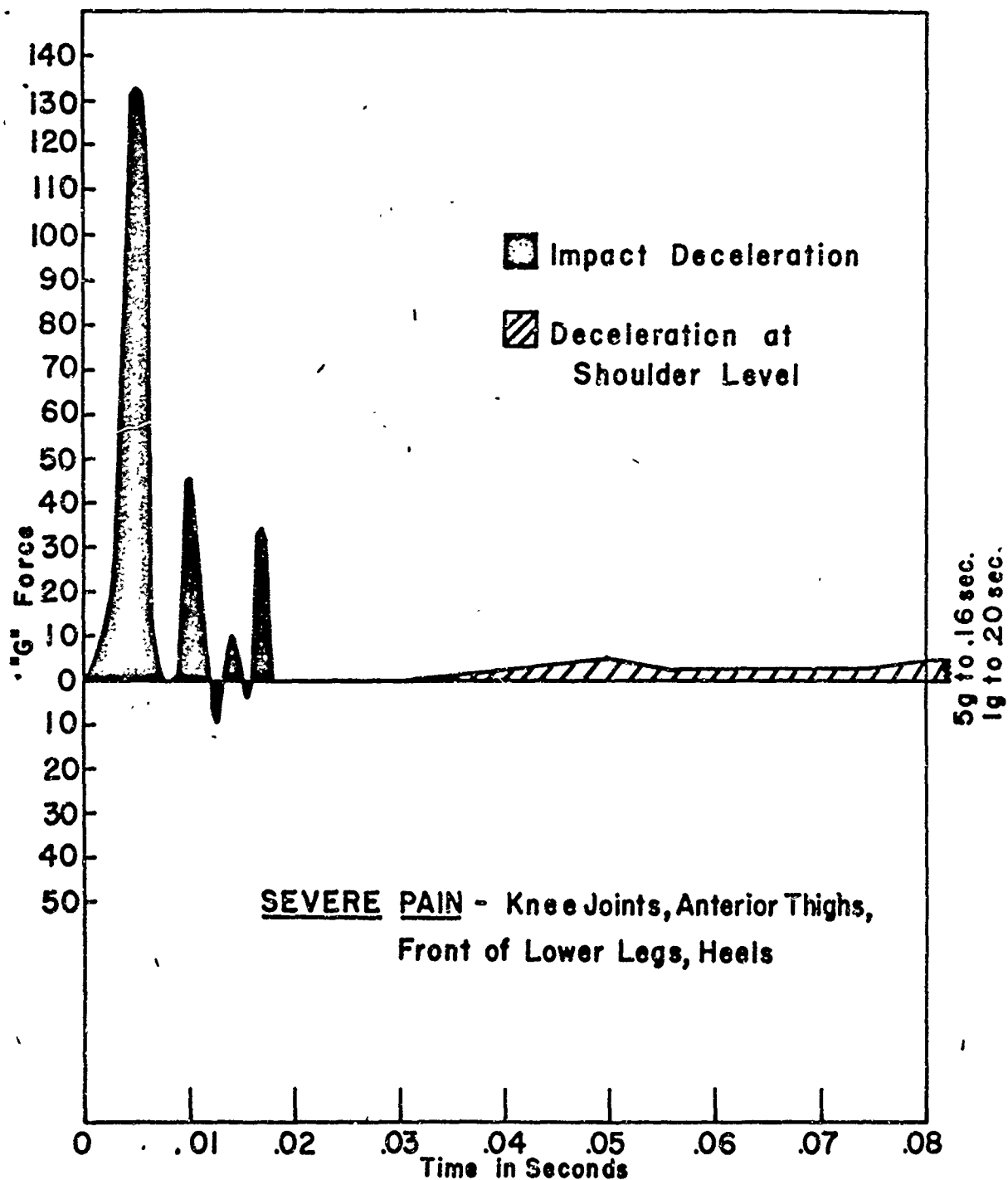


Figure II VERTICAL IMPACT DECELERATIONS
Squatting Position

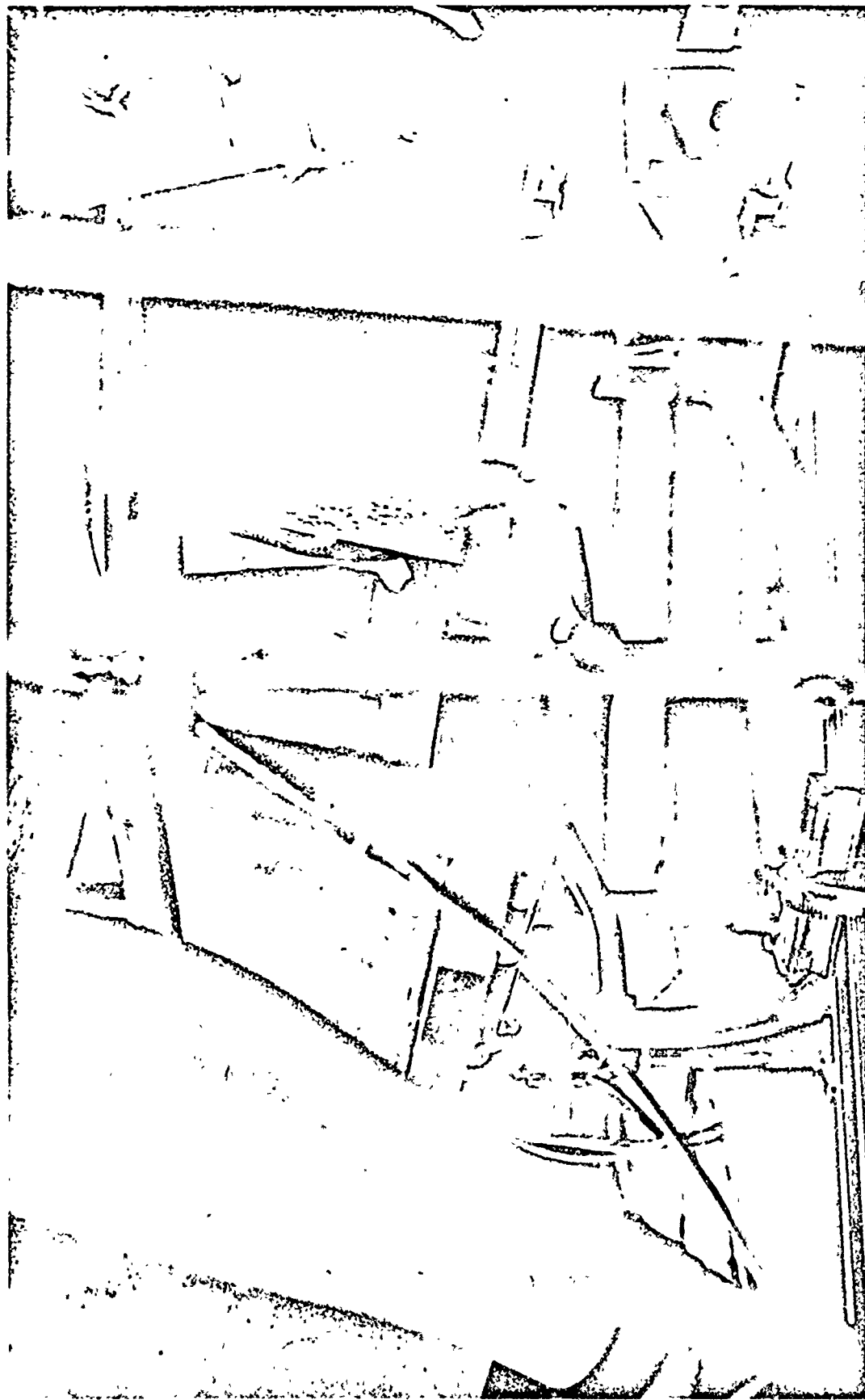


FIG. 12. Test seat equipped with a single block of stayfoam.

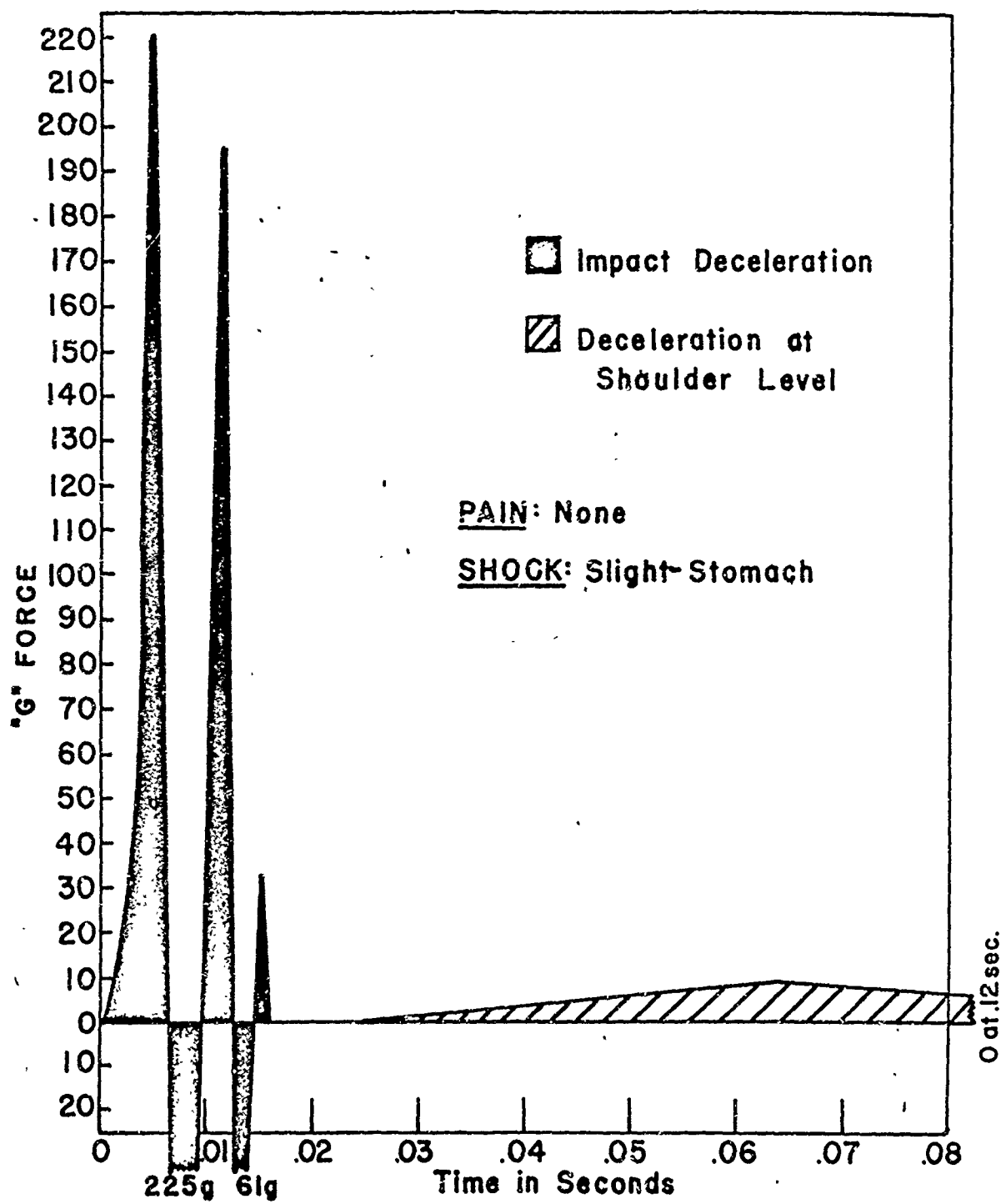


Figure 13 VERTICAL IMPACT DECELERATIONS
Seated in Chair Equipped With Stafoam